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published in

IEA 2000 / HFES 2000 Congress
2000

[Link to publication in VU Research Portal](#)

citation for published version (APA)

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BACK COMPRESSIVE AND SHEAR FORCES DURING CART PUSHING AND PULLING

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Several epidemiological studies suggest that 9-18% of low back injuries are associated with pushing and pulling. Handle height and the direction of the exerted forces (pushing or pulling) are expected to be important determinants of the health risk. The objective of the present study was to investigate the effect of handle height during pushing and pulling on the peak net moments, peak compressive forces and peak shear forces at the L5-S1 level. Handle height was shown to effect low back loading during pushing and pulling.

INTRODUCTION

The manual handling of materials is generally considered as a risk factor for the development of low back complaints. The epidemiological evidence which confirms the relationship between lifting loads and low back pain is substantial. Pushing and pulling have often been suggested as risk factors for musculoskeletal complaints, but pushing and pulling have not been the primary subject of epidemiological studies (Kuiper *et al.* 1999). Several epidemiological studies suggest that 9-18% of low back injuries are associated with pushing and pulling (Hoozemans *et al.* 1998). It was estimated that nearly half of all manual materials handling (MMH) consists of pushing and pulling (Baril-Gingras and Lortie 1995). Furthermore, the contribution of pushing and pulling will increase because of ergonomic interventions aimed at reducing lifting loads by introducing manual handling devices.

The handle height and the direction of the exerted forces (pushing or pulling) appear to be important risk factors of pushing and pulling in relation to musculoskeletal complaints (Hoozemans *et al.* 1998). Although the etiology of low back problems is still unknown, compressive and shear forces on low back structures may be a contributive factor. Therefore, it is of interest to know the compressive and shear forces on the low back during pushing and pulling.

So far, with respect to pushing and pulling, the load on the low back has mainly been estimated using net moments and single equivalent muscle models (SEM, e.g. Lee *et al.* 1991). It might be assumed that for pushing and pulling the validity of such models is low (Lee *et al.* 1989, Andres and Chaffin 1991). Because antagonistic co-activity is to be expected during these activities, the application of an EMG assisted lumbar spine model may reveal new insights (Van Dieën 1997). Therefore, the objective of the present study was to quantify the effect of handle height and direction of the exerted forces during pushing and pulling with respect to peak net moments, peak compressive forces, and peak shear forces at the L5-S1 level using an EMG assisted model.

METHODS

Subjects

Seven healthy male subjects, age 34 (range 25-43) years, length 1.78 (SD 0.12) m, body mass 76.2 (SD 18.1) kg, participated in the experiments. They were all experienced in daily pushing and pulling at work. All subjects gave informed consent prior to the experiments and reported no history of low back pain or other musculoskeletal problems.

Tasks and procedures

Preliminary field studies using on-site observations provided information of frequent pushing and pulling activities during pre-selected physically demanding professions. The most frequent pushing and pulling activities were simulated at the laboratory. A standard four-wheeled cart used in postal distribution centers was used in the experiments. The total weight of the cart was 320 kg. The participants were instructed to push or pull the cart symmetrically with both hands at hip height, 0.91 (SD 0.05) m, or at shoulder height, 1.46 (SD 0.10) m. For each condition, i.e. pushing or pulling at hip or shoulder height, the participants had to displace the cart over a distance of four meters, from and until standstill. The participants were allowed to perform a few practice trials before the actual measurements started. The different conditions were presented in random order.

External forces and kinematics

Two 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) were attached to the cart to assess the exerted forces. LED markers were attached to the left and right side of the body at the L5-S1 joint. Furthermore, markers were attached at the shoulders, thorax, elbows, and the cart. Marker positions were recorded using

The handles were replaced by handles attached to 3-D force transducers (Amti). One container was used to create 9 conditions with different COM locations, using foam and concrete blocks. The other container was used to create 11 conditions with different handle locations with the aid of aluminium bars, attached to the container. COM locations were measured using a force platform (Kistler). The mass of container plus load was 59.5 ± 0.9 kg over the COM conditions and constant at 59.4 kg for the handle conditions.

Tasks and procedures

After practising the condition, the subjects were instructed to grab the handles of the container, to tilt the container and walk backwards with the container at a normal constant speed and with the upper body as symmetrical as possible over a distance of about 5 m. About 1 min later, the subjects were asked to tilt the container, and walk the same trajectory in forward direction while pushing the container symmetrically at a constant speed.

LED markers were attached to the left and right side of the body at the L5/S1 joint, the acromion, and at the wrist. Markers were also attached to the left and right side of the container. Marker positions were recorded using an optoelectronic system (Optotrak). Forces and marker positions were sampled at 50 Hz. From the 5 m walking trajectory, about the middle 3 m was selected for averaging marker positions and forces over time.

Biomechanical model

Time-averaged sagittal plane marker co-ordinates and forces were used as input for an upper body static 2-D linked segment model. The model consisted of four segments: hands, forearms, upper arms and trunk plus head. Reactive forces and torques were calculated at the elbow, shoulder and lumbosacral joints.

Statistical analyses

ANOVAs were applied with subject, pushing/pulling activity and either COM condition or handle condition as independent variables. The dependent variables were averaged values over the 3 m walking trajectory of the container tilt angle, handle height, horizontal and vertical force applied at the handles, as well as for the torques at the elbow, shoulder and lumbosacral joint. ANOVAs with the same independent variables were applied to the peak values of the horizontal and vertical forces at the initiation of the tilting of the container. A p-value of 0.05 was considered significant.

RESULTS

Horizontal force at the handle

The initial horizontal force, required to tilt the container ranged up to about 200 N in some conditions (figure 2a). Due to the moment arm with respect to the axis of the

wheels, the magnitude of these forces strongly depended on the horizontal location of the COM (figure 2a) and to a lesser extent on the handle height (figure 2b). The vertical location of the COM did not influence the initial horizontal tilting forces due to the fact that vertical displacement does not affect the effective moment arm of the COM in the not-tilted position.

Effect of COM on tilt angle, forces and joint loading

It was expected in this study that, given a certain COM location, subjects would manipulate the tilt angle of the container in order to reduce the required vertical force, or to get it at a desired level that would result in a minimum loading of one or more joints. However, it appeared that the container tilt angle was more dependent on the subject than on the COM (figure 2c). As a consequence, the vertical forces during pushing and pulling were highly dependent on the COM location of the container. More forward (i.e. at a larger distance from the subject) and lower locations of the COM resulted in negative (downward) changes of the vertical force (figure 2e).

The COM location had a large effect on the joint torques (figures 2g, 2i and 2k). Roughly, these changes can be explained by the changes in vertical force, since, assuming that the shoulders are not in front of the handles, adding a downward force component at the hands must result in a more extending torque in the elbow and shoulder joint and a less extending torque at the lumbosacral joint. However, with pushing this effect was not consistent at the shoulder joint (figure 2i). This might be related to a postural change, since a significant effect of COM condition on the trunk and upper arm angle was found. While pushing, subjects were 'leaning on the handles' when large downward forces were required. In this way, the reactive forces at the hand nearly pointed at the shoulder joint, so that only small joint torques occurred. In this way, body mass instead of muscle force can be used to produce the downward force by leaning on the handles.

Effect of handle on tilt angle, forces and joint loading

Compared to the COM conditions, the handle conditions had much more influence on the tilt angle of the container (figure 2d). Higher and more forward (at a larger distance from the subject) locations of the handles were associated with a larger tilt angle. However, this increase in tilt angle only partially compensated for the increased handle height, since there was still a significant effect of handle condition on the height of the handle during pushing and pulling. On average, the highest handle locations resulted in a pushing and pulling height of about 18 cm higher in comparison with the lowest handle locations. As a result of the increased tilt angle, the COM of the tilted container was more backward (towards the subject) with respect to the axis of the wheels, resulting in a change of the vertical force in less downward or more upward direction (figure 2f). Consequently, the extending torque at the elbow joint (figure 2h) decreased (in pushing and pulling) and shifted to a flexion torque for the highest handle locations (mainly in pulling).

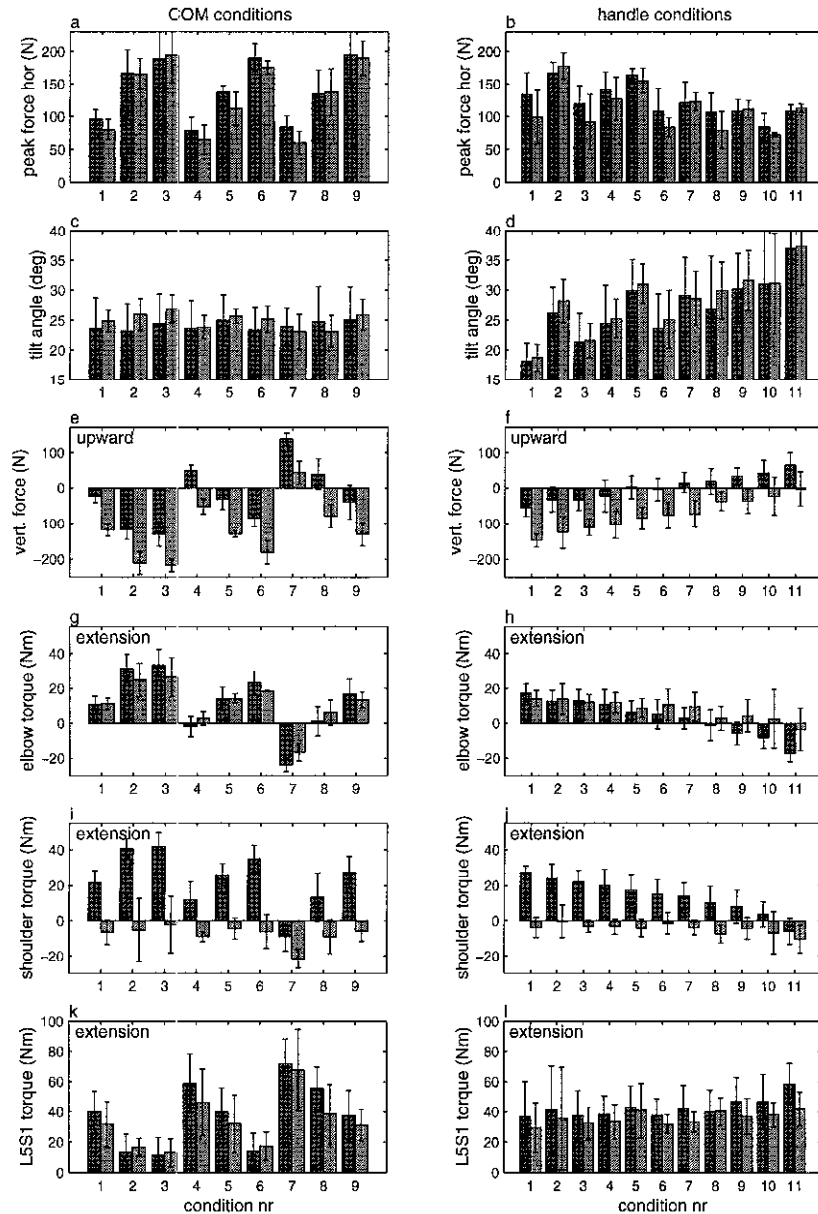


Figure 2. Effect of 9 COM and 11 handle locations on horizontal peak force, tilt angle, vertical force, elbow torque, shoulder torque and L5S1 torque for pulling (1st dark bar) and pushing (2nd light bar)

In addition, the extending torque at the shoulder joint decreased with forward and upward displacement of the handle during pulling, whereas changes during pushing were marginal (figure 2j). Furthermore, the extending torque at the lumbosacral joint slightly increased from low to high handle locations (figure 2l). Despite some postural changes (in terms of trunk and forearm angle) due to the changes of handle location, the trend in changes of joint loading (figures 2h, 2j and 2l) was in line with the change of the vertical force (figure 2f), i.e. a more upward directed force applied to the handle resulted in a decrease of extension torques in the elbow and shoulder and in an increase of the extension torque at the lumbosacral joint.

DISCUSSION

COM location and mechanical loading

Surprisingly, we only found a small influence of the COM location of the container on the tilt angle. Contrary to expectations, subjects hardly adapted the angle of pulling or pushing when the angle of mechanical equilibrium of the container changed. Consequently, the vertical forces, applied to the handle, and the loading of the joints were highly dependent on the COM location. Especially the combination of a downward force and a pulling force can result in a total

force vector that is nearly perpendicular to the orientation of the arm, causing a large moment arm with respect to the shoulder joint. This may cause large shoulder torques even when the downward force only has a moderate magnitude. In the current study, such a situation occurred when the COM was located low and forward (see figure 2, conditions 2, 3 and 6). In pushing, a comparable effect was encountered when the COM was located high and backward at the same time. This can be seen in condition 7 where a combination of pushing and a small upward (lifting) force resulted in large moment arms. These examples show that the COM, which can easily be influenced through the design of the container, is a major determinant of joint loading in pushing and pulling of two-wheeled containers. In addition, it can be concluded that the magnitude of the force applied at the handles is not a good indicator of the mechanical loading of the joints. The direction of this force as well as the position of the joints should be taken into account too.

Handle location and mechanical loading

The finding of a reduction of shoulder joint loading with pulling at increasing handle height, as found in the current study, is in agreement with findings using four-wheeled carts (Hoozemans *et al.* 1998, De Looze *et al.* in press), but the magnitude of the effect is larger. Okunribido and Haslegrave (1999) reported for two-wheeled trolleys that handle height did affect the tilt angle of the trolley but that subjects always tilted the trolley at such an angle that one specific grip height was obtained, regardless of other conditions. In the current study a change of handle height also affected the tilt angle, but not to such an extent that equal handle heights were obtained after tilting. Okunribido and Haslegrave (1999) suggested that the high COM of the trolleys that were studied, may have caused their finding of a constant grip height and this may explain the difference with the current study.

Comparable to a relatively forward located COM, low handle locations resulted in unfavourable combinations of horizontal and vertical forces: a combination of pulling with only small downward forces resulted in relatively high shoulder loading through large moment arms.

Can the design of refuse containers be improved ?

With homogeneous loading, the COM of the container is normally situated about the midline of the container. Thus, conditions 8 and 5 (figure 1) represent COM's for the current container design. In comparison with condition 8, a forward displacement of the COM (to condition 9) decreases the low back loading at the expense of increased elbow and shoulder loading. Conversely, backward displacement (condition 7) increased low back loading without reducing elbow and shoulder loading in an absolute sense. In addition, forward displacement results in high upward forces during pulling and backward displacement results in high downward forces during pushing. The only displacement of the COM that does not have adverse effects on either the vertical force or on the loading of one of the joints, is a displacement in the direction of the axis of the wheels (condition 4). Although such a dis-

placement of the COM provides only marginal changes in terms of joint loading, any downward displacement of the COM improves the stability of the container, which is an argument in favour of condition 4. The reason for this improvement is a reduction of the moment arm of the COM with respect to the axis. Consequently, disturbances of mechanical equilibrium, which constantly occur during pushing and pulling a container on an irregular surface, require less force adaptation to restore the tilt angle. Furthermore, any handling of a two-wheeled container starts with tilting it. Starting at any COM location, displacing this location in the direction of the axis of the wheels results in a proportional decline of the required initial tilting force. For instance, a displacement of the COM from location 8 to location 4 roughly halves the required tilting force (figure 2a).

It can be concluded that a displacement of the COM of the loaded container in the direction of the axis improves the stability and reduces the required tilting forces without negatively affecting vertical forces or joint loading during steady pushing or pulling. One way to achieve this is to make the container wider and, at the same time, place the axis more forward.

It was already mentioned that interaction effects between COM and handle changes were not investigated in the current study. However, as long as the COM changes are along a line towards the axis of the wheels, such interaction effects are not likely to be large. Compared to the current handle location (condition 4), some increase of the height of the handle (condition 6 and 7) did reduce the average vertical forces and the loading of the elbow and shoulder joint, without adverse effects on low back loading. However, we should take care in interpreting averages here, since subject with handle location interaction effects were seen in tilt angle, shoulder loading and low back loading. A more than 10 cm increase of the handle height causes short subjects to tilt the container quite far, resulting in increasing joint loading. In addition, the effects of increased handle height should be studied during one-handed pulling, especially with respect to the loading of the shoulder joint, since extreme shoulder extension might occur when short subjects pull a too high handle with one hand. This requires a detailed 3D analysis.

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